Research Article

CONSTRAINED FORMATION OF OBJECT REPRESENTATIONS

Kevin J. O'Connor and Mary C. Potter
Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology

Abstract—*Viewers were presented with a rapid sequence of very brief stimulus pairs, each of which consisted of a pictured object followed by a related or unrelated word. The form of relatedness between the picture and word was manipulated across experiments (identical concept, associated concept, ink color of the picture). Recognition memory for the pictures was affected not only by whether or not paired items were conceptually identical or semantically related, but also by whether or not the words named an irrelevant feature, ink color. These results show that sequential items are integrated on the basis of similarity at whatever level is available, so that the stability of the memory representation of one or both items is increased. We propose that a common mechanism may underlie integration, priming, and selective attention.*

A central feature of the visual system is its ability to efficiently integrate a discontinuous input stream from the environment into a coherent, meaningful representation. The discontinuity arises from several sources, including saccadic eye movements and object occlusion and transformation. The apparent ease with which observers are able to resolve the complex problem posed by the environment shows that the human visual system can rapidly integrate disparate pieces of information.

In the laboratory, evidence for such integration comes from studies of comprehension of rapid serial visual presentation (RSVP) sentences. At a very high rate of presentation (12 words/s), viewers can process sentences, integrating each word as it is encountered into a reportable conceptual representation (Potter, 1982, 1993). The formation of these representations is constrained by multiple sources of information, such as lexical and conceptual associations among words, syntactic structuring rules, and sentence plausibility (Gibson & Pearlmutter, 1998).

When, however, there is no "thread" to link items and guide formation of high-level representations, integration cannot occur, and each item "conceptually masks" the preceding one (Potter, 1976). This has been demonstrated in studies of memory for RSVP lists of unrelated words (Potter, 1982) and pictures (Potter & Levy, 1969). These studies have shown that although each item is recognized as it is encountered, the items cannot be integrated into a single conceptual representation, and memory for individual stimuli is very poor.

According to Potter (1993, 1999), the processing domain in which visual stimuli are integrated into higher-order conceptual representations is conceptual short-term memory (CSTM). Functionally, this model describes the processing occurring within the first several hundred milliseconds following stimulus presentation and is considered distinct from slower, more consciously controlled short-term memory domains, such as working memory. In CSTM, visual inputs are quickly represented up to a conceptual level and are potentially integrated as part of higher-order representations. Representations in CSTM are hypothesized to be volatile, and only information integrated into higher-order structures is stabilized and retained in working or long-term memory, whereas information not integrated rapidly decays and is forgotten.

Integration and forgetting, phenomena representing the extremes of a single CSTM processing continuum, have both been demonstrated for words—in studies of sentence processing and word-list memorization, respectively (Potter, 1982). Nonverbal items such as objects or scenes, however, have mainly been used in studies investigating the rapid-forgetting end of this continuum (e.g., Potter & Levy, 1969).

In the current experiments, we examined the interaction between a briefly viewed picture and a following word, on the assumption that verbal and pictorial information are represented conceptually in the same format (e.g., Potter & Faulconer, 1975; Snodgrass & McClure, 1975) and interact in priming contexts (Dell'Acqua & Grainger, 1999). We varied the degree to which the verbal information was convergent with various dimensions of the preceding object representation.

EXPERIMENT 1

The purpose of this study was to determine if memory for a briefly viewed object is affected when the object is immediately followed by a conceptually related word. If so, this would suggest that the early processing responsible for the formation and stabilization of object representations continues after stimulus presentation and can be influenced by the coincident processing of relevant information.

The experiment had two parts: a study phase and a test phase. In the study phase, participants viewed a rapidly presented sequence of stimulus pairs, each of which consisted of an object drawing immediately followed by a word embedded in a mask. The word either named or was unrelated to the object preceding it. Participants were instructed to simply attempt to process each stimulus as it was presented.

After viewing the series, participants were given an unexpected memory test of the pictured objects. We predicted that the objects immediately followed by their names would be recognized more readily than those followed by unrelated words.

Method

Participants

Fourteen volunteers from the MIT community were paid for their participation. All were native English speakers. Three additional subjects were excluded: 2 because of below-chance recognition performance, and 1 because of a computer error.

Materials and apparatus

The object stimuli used in the two phases were a set of 108 black-and-white line drawings of objects selected from the Snodgrass and Vanderwart (1980) materials. The words used were the 108 names of

Address correspondence to Kevin O'Connor, Department of Brain and Cognitive Sciences, MIT Building NE20-439, 77 Massachusetts Ave., Cambridge, MA 02139; e-mail: kj_oc@yahoo.com.

these objects. The computerized drawings were presented on a gray background (software settings of 100 for red, blue, and green) in an area approximately 9 cm × 9 cm (8.5° × 8.5° viewed from approximately 60 cm). Words were presented in a white, 24-point Helvetica font. They were centered in a background-colored rectangle surrounded by a masking stimulus. The mask was approximately the same size as the object stimuli. The names of the objects are listed in the appendix. This and the other experiments reported here were conducted on a Macintosh computer using MacProbe software (Hunt, 1994).

Design and procedure

Each stimulus unit in the study phase consisted of the following sequence: mask for 400 ms, object for 40 ms, and word-plus-mask for 53 ms (illustrated in Fig. 1). A continuous sequence of 18 such units was presented in each of four blocks; each block ended with a 400-ms mask. Consecutive blocks were separated by a blank screen for approximately 3 s. For each subject, 72 objects were selected at random from the entire set of 108 images. Of these 72 objects, 36 were randomly selected to be in the related condition. The remaining 36 objects and their names were re-paired randomly. Thus, although unrelated words did not name their directly paired objects, they did name other objects in the series. This ensured that any observed differences in memory performance between the related and unrelated conditions would be due to the temporally contiguous processing of related objects and words, rather than simply to the presence of a related word somewhere in the sequence.

The presentation order of the 72 stimulus pairs was randomized. Participants were told that they would be viewing a series of very briefly presented words and objects, their task was to pay close attention to all items in the series, and they would receive further instructions after viewing the series.

The test phase, which occurred after all 72 stimulus pairs had been presented, was a series of 108 object recognition trials (72 studied and 36 new objects). Each trial began with a fixation point presented for 400 ms, followed by an object drawing presented for 400 ms. Participants responded by pressing one of two keys to indicate whether the drawing was old (seen in the study phase) or new. The next trial began immediately after the response. Participants were instructed to respond rapidly and accurately.

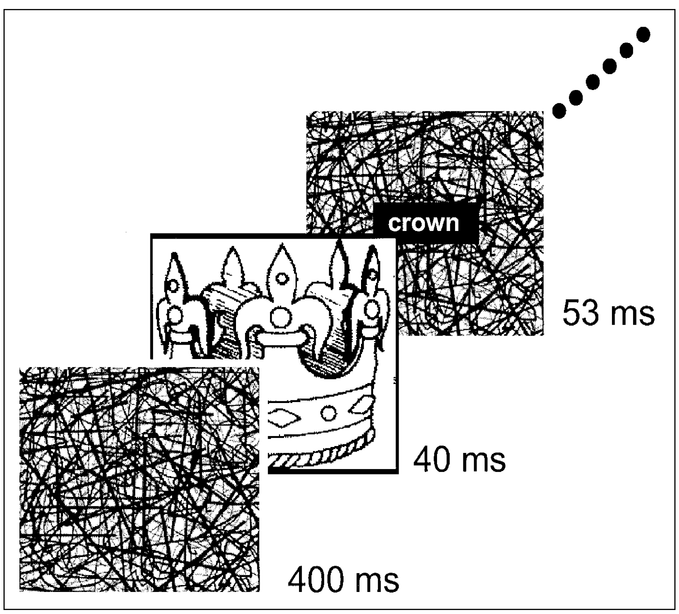

Fig. 1. Schematic illustration of the experimental paradigm used in Experiment 1.

Results and Discussion

Memory performance was assessed by calculating d' for the related and unrelated conditions, separately for each subject. The d' scores, shown in Figure 2, were analyzed in an analysis of variance (ANOVA) with one factor, condition (related or unrelated). Although performance was low in both conditions (related items: mean $d' = 0.641$, mean $\beta = 1.33$; unrelated items: mean $d' = 0.484$, mean $\beta = 1.33$), a significant memory advantage for objects in the related condition was observed, $F(1, 13) = 5.91$, $p < .05$.

Experiment 1 demonstrated that differential recognition memory for objects can be obtained when an object is accompanied at encoding with a word that names it. These results also demonstrate that it is not merely the presence of the picture's name somewhere in the sequence that is responsible for the effect, but rather the juxtaposition of the picture and word.

The results do not show whether this effect was due to the influence of the word representation on the object representation or vice versa. Participants' recognition performance may have reflected memory for the actual object exemplars, or it may have reflected enhanced memory for words related to a preceding picture. That is, subjects may have named the pictures in the recognition test and then recalled the words when making their decision. To separate object and word memory, in Experiment 2 we used words that were close conceptual associates of the objects.

EXPERIMENT 2

In Experiment 2, the related words were close associates of the objects. We predicted that the related words would help to stabilize the

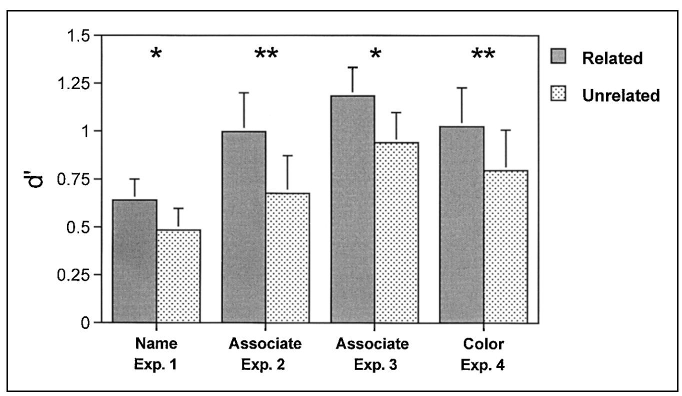

Fig. 2. Recognition results of Experiments 1 through 4. Recognition was tested with pictures in Experiments 1, 2, and 4, and with the names of the pictures in Experiment 3. The label for each experiment indicates the type of word paired with each object. Error bars show standard errors. The significance of the difference between the related and unrelated conditions is shown by asterisks: $*p < .05$, $**p < .01$. Exp. = Experiment.

object representations, increasing the likelihood the objects would be recognized later. The method was like that of Experiment 1 except as noted.

Method

Participants

Nine participants were drawn from the MIT community; all were native English speakers. None had participated in Experiment 1. One additional participant was excluded because of below-chance performance.

Materials

The same pictures used in Experiment 1 were used for this experiment. The majority of the words were close associates of the objects obtained from the free association norms of Nelson, McEvoy, and Schreiber (1998). The remaining associates were generated by the experimenter and evaluated in a pilot survey. The object-word pairs used in this experiment are given in the appendix.

Design and procedure

Because overall memory performance was relatively low in Experiment 1, in Experiment 2 we increased the presentation durations in the study phase from 40 to 67 ms for objects and from 53 to 107 ms for words.

Results and Discussion

The results are shown in Figure 2. Overall performance was somewhat higher than in Experiment 1, consistent with the increase in presentation duration. The d' results were analyzed in a one-factor ANOVA. There was a significant effect of condition, $F(1, 8) = 19.38$, $p < .01$, with memory performance higher in the related condition (mean $d' = 0.997$, mean $\beta = 1.39$) than in the unrelated condition (mean $d' = 0.678$, mean $\beta = 1.41$).

Experiment 2 shows that memory for briefly presented objects is influenced when, at encoding, a word conceptually related to an object is presented immediately after the object is presented. In Experiment 1, objects and words were directly related to the same high-level concept, and thus it was unclear whether the memory trace influenced by relatedness among stimuli represented the object, the following word, or both. Experiment 2, however, suggests that at least a component of the effect can be attributed to enhancement of the object representation, and not simply memory for the word itself.

It is possible, however, that the better memory for objects in the related condition was due to better initial object identification, given the presence of a related word. To examine this issue, we carried out two control experiments using the stimulus pairs of Experiment 2. In each control experiment, the trials were matched to those of the 9 subjects in Experiment 2; viewers reported the identity of the picture immediately after each presentation of a picture-word pair and its following mask (each trial consisted of a premask for 400 ms, a picture for 67 ms, a word for 107 ms, a final mask of 400 ms, and a prompt to enter the object's name). In the first control experiment, Experiment 2a, the words were replaced by a row of *x*s; in the second control experiment, Experiment 2b, the picture-word pairs were the same as those presented in Experiment 2, with related and unrelated pairs intermingled as before. Each experiment had 9 new participants.

Strikingly, recognition performance was high in both control experiments. In Experiment 2a, 93% of the pictures from both conditions (i.e., related and unrelated) were correctly recognized. In Experiment 2b, however, 97% of the pictures in the related condition were recognized, compared with 93% in the unrelated condition, $t(8) = 3.25$, $p < .05$. These results suggest that related information does influence the initial stages of object recognition and stabilization, but also suggest that the presentation times in Experiment 1 were usually sufficient for initial identification of the pictures in both conditions.

EXPERIMENT 3

What is the nature of the enhanced representation responsible for the improved object memory demonstrated in Experiments 1 and 2? Is it pictorial or conceptual? In Experiment 3 we replicated Experiment 2, but the memory test consisted of the names of the objects, rather than the pictures. Note that these words had not been presented in the study phase; the words in the study phase were merely associates of the pictures. If the representations underlying object recognition are primarily pictorial, name recognition should be poorer overall than picture recognition. If, however, these representations are conceptual, no difference in memory performance between Experiments 2 and 3 would be expected.

Method

The method was like that of Experiment 2, except as specified.

Participants

Participants were 11 paid volunteers from the MIT community. None had participated in the previous experiments. One additional subject was excluded because of below-chance performance.

Materials

The materials used in this experiment were the same as in Experiment 2, except the recognition test consisted of the names of the pictures.

Design and procedure

The procedure was identical to that of Experiment 2, with the exception that the names of the pictured objects, rather than the pictures, were used in the recognition test.

Results and Discussion

An analysis of d' revealed a significant effect for condition, $F(1, 9) = 7.64$, $p < .05$ (related items: mean $d' = 1.184$, mean $\beta = 2.16$; unrelated items: mean $d' = 0.939$, mean $\beta = 2.25$; see Fig. 2). In a between-subjects ANOVA of Experiments 2 and 3, the main effect of experiment was not significant, $F < 1$. The difference between conditions was significant, $F(1, 17) = 23.34$, $p < .01$, but the interaction between experiment and condition was not, $F < 1$.

The results indicate that although the representations underlying memory in the present experiments may include featural information, such information is not necessary to cue subsequent recollection. The fact that memory could be cued equally well by names and pictures suggests that the pictures were encoded as conceptual entities. Given the demanding nature of the study phase, in which viewers were required to process objects and words rapidly, it is possible subjects adopted a strategy of encoding the common, conceptual dimension of both stimulus types. This finding is consistent with the results of a study by Snodgrass and McClure (1975), in which names and pictures were recognized equally well, although the fact that subjects in that experiment studied all picture-word pairs in advance may have biased subjects toward a common code.

Is the observed interaction between objects and words necessarily limited to conceptually convergent representations, or is it possible this effect may be found for other forms of convergence, such as between a feature of a drawing—for example, its color—and a word? We investigated this question in Experiment 4.

EXPERIMENT 4

We conducted Experiment 4 to determine whether a word related to a visual feature of an immediately preceding object can influence subsequent object memory. The feature manipulated was the color of the drawings. In the previous experiments, the pictures were black drawings on white backgrounds. In Experiment 4, three different colors were used. The word presented after each object named one of these colors. In the related condition, this color word named the drawing color. In the unrelated condition, the word named one of the two other colors. If the observed effect of object-word convergence on memory extends to feature-related information, recognition memory should be better for objects paired with matching color words than for objects paired with nonmatching color words. Critically, the recognition test used black-and-white drawings. Thus, no color cue was present during the memory test.

Method

The method was like that of Experiment 2 except as specified.

Participants

Participants were 9 paid volunteers from the MIT community. None had participated in the previous experiments. All were native English speakers.

Materials

In the presentation phase, each object was rendered in one of three randomly assigned colors: red (software settings: red—255, green—0, blue—0), green (software settings: red—24, green—231, blue—24), or blue (software settings: red—0, green—0, blue—255). All drawings were presented on a white background. Luminance values for the three colors and the white background were as follows: red—22.16 cd/m^2, green—62.90 cd/m^2, blue—15.58 cd/m^2, and background—110.09 cd/m^2. During the test phase, black-and-white object drawings were used.

Design and procedure

The procedure was identical to that of Experiment 2 except that objects in the study phase were rendered in one of three colors and were followed by one of three color naming words.

As in the preceding experiments, 72 objects in the study phase were divided randomly between two conditions, related and unrelated. In each of the two conditions, the color in which each object was rendered was determined randomly for each subject. The three colors were used equally often. In the related condition, the color word following the object matched the object's color. In the unrelated condition, the color word did not match the object's color. Each mismatching color word was represented equally often.

The test phase was identical to that of Experiment 2; all test pictures were black on white.

Results and Discussion

Memory performance, measured by d', was analyzed in a one-factor ANOVA. This analysis revealed a significant effect for condition, $F(1, 8) = 13.78$, $p < .01$ (related colors: mean $d' = 1.024$, mean $\beta = 1.97$; unrelated colors: mean $d' = 0.795$, mean $\beta = 1.82$; see Fig. 2). Because the three colors differed in luminance, subjects' performance as a function of color and condition was also analyzed in a separate two-factor ANOVA (see Fig. 3). In this analysis, performance was assessed as the number of correct recognition responses for pictures from each color group in each condition. Results of the analysis revealed, once again, a significant main effect for relatedness, $F(1, 9) = 8.67$, $p < .05$, and a significant main effect of color, $F(2, 16) = 13.13$, $p < .05$. There was no interaction between condition and color, $F < 1$. Pair-wise comparisons of overall performance for each object color revealed that objects presented in green were remembered less often than both those presented in red, $t(8) = -2.58$, $p < .05$, and those presented in blue, $t(8) = -2.3$, $p < .05$. This effect was very likely due to the lower image contrast for green objects relative to red and blue objects (green: .429; red: .799; blue: .858).

These results show that a word naming an arbitrary, semantically insignificant feature (color) of a drawing can strengthen picture memory (relative to a mismatching word) even though memory is assessed using a black-and-white version of the drawing. That is, convergence between the superficial color feature of an object and a color word improved object memory. Evidently, the word's relatedness at encoding to an arbitrary dimension benefited the entire object representation, not just that irrelevant dimension. This effect was replicated in an additional experiment in which object color and presentation order were

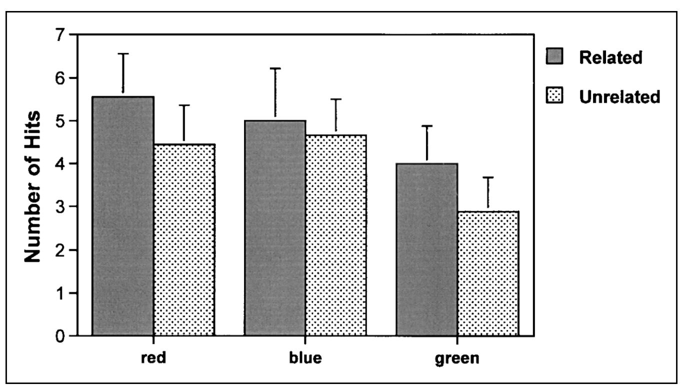

Fig. 3. Average number of correctly recognized objects (hits) in Experiment 4 by presentation color and condition. Error bars show standard errors.

counterbalanced across subjects rather than randomized independently for each subject.

GENERAL DISCUSSION

The current studies tested a prediction that stabilization, or consolidation, of an object representation can be influenced by additional information presented immediately after the object. Specifically, we predicted that if a word was related to some dimension of an object representation, this convergent information would serve to guide, or facilitate, the formation of the object representation, much as convergent information serves to constrain the formation of conceptual representations in on-line sentence comprehension. This facilitation, we hypothesized, would render these object representations more stable than representations accompanied by irrelevant information. Such increased stability should be reflected in memory for these objects.

Experiments 1 through 3 demonstrated that relatedness between object and word at the conceptual level does lead to a memory advantage for objects. In particular, Experiment 3 showed this advantage is seen in tests of conceptual object memory. These findings are consistent with Potter's (1999) CSTM framework, and extend this model to include objects as entities whose conceptual representations can be stabilized by additional related information.

Experiment 4 demonstrated that this effect of convergence is not limited to the conceptual dimension of objects. This experiment generalized the findings of Experiments 1 through 3 by demonstrating that relatedness between a word and a nonconceptual dimension of an object representation, specifically its superficial color, can result in the same type of memory advantage as observed in the first three experiments.

These findings are consistent with object-based processing and attention (e.g., Luck & Vogel, 1997) extended to integration over time rather than space. That is, the structuring of representations may be guided by dimensions shared by successive as well as concurrent inputs. Such processing, seen in high-level visual cognition in a task such as comprehending an RSVP sentence, may more generally characterize the nature of numerous levels of representational structuring. In lower-level vision, integration of inputs over time is central to the construction of perceptual representations (e.g., Eagleman & Sejnowski, 2000; Morrone, Burr, & Valna, 1995; Neri, Morrone, & Burr, 1998). The current findings involving color, by demonstrating integration at a middle level, suggest that integration may operate continuously, from low-level perceptual inputs up to high-level conceptual representations.

This framework may also be able to shed new light on other phenomena related to the current studies, such as semantic priming. Short-term priming phenomena, occurring for prime-target stimulus onset asynchronies on the order of 10s of milliseconds, have often been hypothesized to be the result of activation in a semantic network spreading from the prime's representation to that of the target (Collins & Loftus, 1975). However, this account has difficulty explaining so-called retroactive priming, in which facilitation of target processing is observed when the prime actually follows the target (Kiger & Glass, 1983). Such cases, which resemble the effects observed in the current studies, have prompted other explanations of short-term priming that could be considered integration theories. For example, Ratcliff and McKoon (1988) proposed that the target and prime, independent of their presentation order, form a compound. Additionally, Briand, den Heyer, and Dannenbring (1988) hypothesized that backward effects are the result of synergistic processing between target and prime. These accounts, as well the current studies, favor an explanation of forward and retroactive semantic priming as resulting from a single active integrative process rather than a passive spread of activation in a semantic network. Furthermore, semantic spreading activation cannot account for interactions among representations sharing nonsemantic dimensions (i.e., color, in the present case), but can be explained as the result of integration constrained by shared information.

Interactions among representations sharing conceptual information serve an important function in the case of reading, but why should interactions occur among representations (e.g., objects and color words) having no conceptual relation to one another? One possible explanation is that such interactions are evidence of the fundamental mechanisms exploited by attentional systems in order to select information from the visual stream. In Desimone and Duncan's (1995) biased-competition model of attentional selection, selection of a given perceptual input occurs when a signal from higher cortical areas serves to strengthen representations possessing a dimension convergent with information coded in this top-down signal (e.g., color, semantic features), resulting in these items' selection. Dark, Vochatzer, and VanVoorhis (1996) described selective attention in a similar manner (see also Bernstein, Bissonnette, Vyas, & Barclay, 1989). Specifically, they posited that selection is an automatic effect of convergence between the current state of the visual system and its inputs. This effect theory of attention includes the provision that the state of the system can be modulated by high-level systems. Recent experiments (Downing, 2000; Pashler & Shiu, 1999) have provided evidence of top-down biased processing in humans by showing that active maintenance of a representation in working memory leads to automatic selection of matching visual inputs.

Selection, in the current context, can be seen as an operation resulting in the stabilization of specific representations at the expense of others. Given that the present study demonstrates stabilization of object representations via convergence of dimensions along which attention is able to select, it is possible that these effects are the result of the same processes underlying deliberate selection. Selection may result from convergence between an actively maintained attentional set and a single input, instead of from relatedness between two inputs. Selection may therefore exploit a general attribute of the visual system—its ability to integrate concurrently active representations automatically along their related dimensions, such that they are stabilized and are subsequently able to enter higher levels of processing.

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APPENDIX: OBJECTS USED IN EXPERIMENTS 1 THROUGH 4 AND ASSOCIATES USED IN EXPERIMENTS 2 AND 3

Object	Associate	Object	Associate	Object	Associate
airplane	flight	crown	king	lamp	light
anchor	boat	cup	saucer	leaf	tree
apple	red	dog	bark	lightbulb	bright
axe	chop	doorknob	grip	lion	roar
ball	bounce	dresser	drawers	monkey	banana
balloon	pop	drum	stick	motorcycle	helmet
barn	farm	duck	quack	mouse	cheese
bear	grizzly	ear	hear	mushroom	fungus
bed	sleep	elephant	trunk	nut	bolt
bee	sting	eye	see	piano	keys
beetle	bug	fish	swim	pig	pork
bell	tower	flag	pole	rabbit	white
bicycle	ride	flower	petals	raccoon	mask
bird	nest	foot	toes	recordplayer	music
book	read	football	kick	ring	finger
boot	stomp	frog	green	sailboat	ocean
bottle	wine	giraffe	neck	sandwich	ham
bow	tie	glasses	frames	saw	wood
bread	butter	gorilla	hairy	scissors	snip
broom	sweep	grapes	vine	sheep	wool
bus	driver	grasshopper	jump	shoe	walk
butterfly	caterpillar	guitar	strum	snail	slow
cake	birthday	gun	shoot	snake	slither
camel	desert	harp	angel	snowman	winter
candle	wax	hat	head	spider	web
car	drive	helicopter	blades	squirrel	nuts
carrot	orange	horn	blow	strawberry	shortcake
cat	meow	horse	saddle	telephone	call
celery	stalk	house	family	train	tracks
chair	sit	iron	clothes	tree	forest
chicken	eggs	kangaroo	pouch	turtle	shell
church	religion	kettle	boil	umbrella	rain
clock	time	key	lock	violin	bow
clothespin	laundry	kite	string	wagon	pull
clown	funny	knife	cut	well	water
cow	milk	ladder	climb	windmill	turn